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Physics Procedia 22 (2011) 381 – 385
Physics Procedia

2011 International Conference on Physics Science and Technology (ICPST 2011)

Thermo-mechanical Characteristics of Smart Skin Antenna Structures

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Abstract

Analysis on the thermo-mechanical behaviors of smart skin antenna structures under air flow is performed. The model is a conformal load-bearing structure, reducing radar cross section and increasing stealth functions are very important. The skin is modeled as a multi-layer sandwich structure composed of carbon/epoxy, glass/epoxy and a dielectric polymer. Furthermore, a dielectric layer is embedded on the middle surface of the sandwich structure to act as antenna or radars. The formulation of the structural model is based on the first-order shear deformation plate theory. Lastly, Newton-Raphson iterative method applied for solving the nonlinear equations of the thermal post-buckling analysis and numerical results are calculated by finite element method.

Selection and/or peer-review under responsibility of Garry Lee.

keywords: Multi-layer sandwich plate; Smart skin structure; Thermal post-buckling

1. Introduction

Throughout the history, researchers have endeavored to develop new and advanced technologies with the goal of achieving military advantage of the materials. Recently, many countries lead to develop so called stealth aircraft in order to avoid radar detection. For this reason, smart skin structures are investigated. The skin is a conformal load-bearing antenna structure reducing radar cross section and increasing stealth function. Finally, the structure is composed of laminated with special properties.

Smart skin structures have been widely investigated such as the design procedure including the structure design, material selection and design of antenna elements in order to obtain high electric and mechanical performances [1]. Kang et al. [2] performed analysis and optimal design of smart skin

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1875-3892 © 2011 Published by Elsevier B.V. Selection and/or peer-review under responsibility of Garry Lee.
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structures for buckling and free vibration using finite element method and genetic algorithm. Yoon et al. [3] designed and fabricated a simple conformal load-bearing smart skin antenna structures. Under the unidirectional compression load, the test and analysis results were compared. Yoo and Kim [4] presented the thermal buckling of the smart skin for the antenna performance and optimization to maximize the critical temperature and natural frequency.

Generally, laminated plate is replaced metal structures for the smart skin of aircraft wings and antenna to reduce the weight of structure. In this work, first-order shear deformation theory is employed and von-Karman strain-displacement relations are based to derive governing equations of the plate. Nonlinear analysis of the structural model in supersonic range is calculated by the first-order piston theory. The Newton-Raphson method is applied to solve the governing equations of the model. The thermal buckling characteristics of the smart skin are studied with design variables.

2. Modeling and formulation

2.1. Modeling

As shown Fig. 1, the smart skin model is introduced. The model is consist of 6 composite plates such as Glass/epoxy, Carbon/epoxy and Dielectric layer. The face sheets protect the dielectric layer due to external disturbances such as aerodynamic force and thermal loading. The carbon/epoxy layer was located on each side of the dielectric layer. Then, the honeycomb cores transmit shear between sheets, and provide the air gap to the antenna. Material Properties are presented in Table 1.

Table 1. Material properties of the smart skin

	G/E	C/E	Phenol	Honeycomb
E_1	24Gpa	67 Gpa	7.2 Gpa	0.09 Mpa
E_2	28 Gpa	57 Gpa		0.08 Mpa
ν_{12}	0.105	0.103	0.3	0.3
G_{12}	4.54 Gpa	5.9 Gpa		0.1 Mpa
G_{13}	1.0 Gpa	1.0 Gpa		19.7 Mpa
G_{23}	1.0 Gpa	1.0 Gpa		11.5 Mpa
α_1	9.7^{-6}/℃	2.1^{-6}/℃		1.5^{-6}/℃
α_2	17.7^{-6}/℃	2.1^{-6}/℃		1.5^{-6}/℃
ρ	2200kg/m^3	1450kg/m^3	9000kg/m^3	96.1kg/m^3

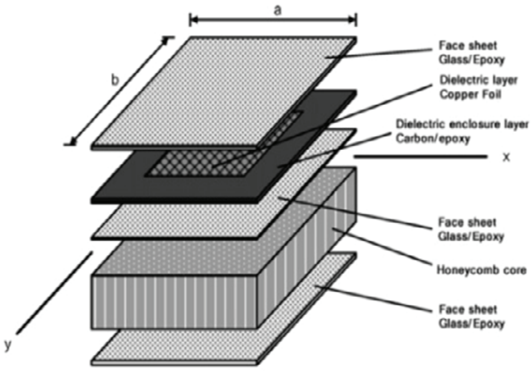

Fig. 1. The model of smart skin structure [3]

2.2. Formulation

The displacement fields for a composite plate based on the first-order shear deformation theory, and the von Karman strain-displacement relations for small strains with moderate rotations.

The stresses with thermal effect in laminate layers for the k^{th} layer are obtained by transformation of coordinates as

$$[\sigma]_k = [\overline{Q}]_k \left(\{\varepsilon\}_k - \Delta T\{\alpha\}_k\right) \tag{1}$$

where $[\overline{Q}]$, ΔT and $\{\alpha\}$ are the transformed stiffness coefficients, temperature rise and thermal expansion coefficients, respectively.

The force and moment resultant vector can be expressed

$$\begin{Bmatrix} N_b \\ M_b \end{Bmatrix} = \begin{bmatrix} A & B \\ B & D \end{bmatrix} \begin{Bmatrix} \varepsilon^0 \\ \kappa \end{Bmatrix} - \begin{Bmatrix} N_{\Delta T} \\ M_{\Delta T} \end{Bmatrix}, \qquad Q = S\gamma \tag{2}$$

where thermal forces $\{N_{\Delta T}\}$ and moment $\{M_{\Delta T}\}$ induced by the temperature change define as $\left(N_{\Delta T}, M_{\Delta T}\right) = \sum_{k=1}^{n} \int_{z_{k-1}}^{z_k} [\overline{Q}]_k \{\alpha_k\}(1,z)\Delta T dz$.

To derive the governing equations, the principle of virtual work is applied.

The internal virtual work is given by

$$\begin{aligned} \delta W_{int} &= \int_V \{\delta e\}^T \{\sigma\} dV = \int_A \{\delta\varepsilon_m\}^T \{N\} + \{\delta\kappa\}^T \{M\} + \{\delta\gamma\}^T \{Q\} dA \\ &= \{\delta d\}^T \left([K] - [K_{\Delta T}] + \tfrac{1}{2}[N1] + \tfrac{1}{3}[N2]\right)\{d\} - \{\delta d\}^T \{P_{\Delta T}\} \end{aligned} \tag{3}$$

where $[K]$, $[K_{\Delta T}]$, $[N1]$, and $[N2]$ represent the linear elastic stiffness, the thermal geometric stiffness, the first-order nonlinear stiffness and the second order nonlinear stiffness matrices, respectively.

The external force in this work is an aerodynamic pressure under a supersonic airflow. It is assumed by first-order piston theory which is valid for $\sqrt{2} < M_\infty < 5$. The aerodynamic pressure is given by

$$p_a(x,y,t) = -\frac{\rho_a V_\infty^2}{\sqrt{M_\infty^2 - 1}} \left\{ \frac{\partial w}{\partial x} + \left(\frac{M_\infty^2 - 2}{M_\infty^2 - 1}\right) \frac{1}{V_\infty} \frac{\partial w}{\partial t} \right\} = -\left(\lambda \frac{D_m}{a^3} \frac{\partial w}{\partial x} + \frac{g_a}{\omega_0} \frac{D_m}{a^4} \frac{\partial w}{\partial t} \right) \tag{4}$$

where V_∞, M_∞ and ρ_a are the air flow speed, mach number and air density, respectively. In addition, non-dimensional aerodynamic pressure is defined as $\lambda = \dfrac{\rho_a V_\infty^2 a^3}{\beta D_m}$.

Finally, the governing equation in matrix form for the present study is obtained as

$$\left([K] - [K_{\Delta T}] + \lambda [A_f] + \frac{1}{2}[N1] + \frac{1}{3}[N2]\right)\{d\} = \{0\} \tag{5}$$

In Eq. (5), the Newton-Raphson method is applied to analyze the post-buckling behaviors of the model.

3. Numerical results and discussions

3.1. Code verification

To verify the code for the thermal buckling analysis, the thermal buckling analysis of a composite sandwich plate structure that is compounded $[0/90/\ldots/90]^{10}$[core] $[90/0/\ldots/0]^{10}$ is performed. Table 2 shows the present result has good agreement with the data in Ref. [5]. The design variables are area of dielectric layer, aspect ratio and aerodynamic load in this work.

3.2. Thermo-mechanical behaviors

Figure 2 shows the post-buckling behaviors with change of area ratio of the dielectric layer. The layer sequence is [θ/- θ]s, and dielectric enclosure layers are made of six composite layers [0/θ/90]s. As the area of dielectric layer is increased, the non-dimensional deflection is increased. It is due to low stiffness characteristics of dielectric layer.

Table 2. Critical Temperature of Laminated Sandwich Plates

a/h	h_f/h	[5]	Present Solution
20	0.05	0.09498	0.094948
	0.1	0.08667	0.088751
	0.15	0.07954	0.072274
	0.2	0.07345	0.061999

Aspect ratio: 1, Stacking Sequence: $[0/90/\ldots/90]^{10}$[core]$[90/0/\ldots/0]^{10}$

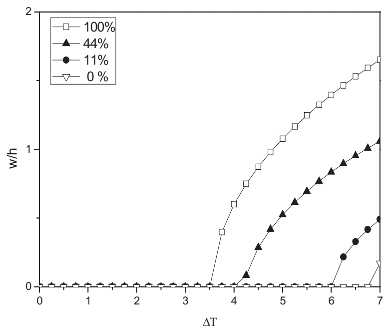

Fig. 2. Behaviors with variation of area ratio

Figure 3 illustrates the characteristics with variation of aspect ratio of the face sheets and dielectric enclosure layer. As the aspect ratio is increased, the non-dimensional deflection is increased. Furthermore, aspect ratio has almost no effect on the behavior for the smart skin structure with aspect ratio greater than 2. Thus, similar results were observed in which the aspect ratio is between 2 and more over.

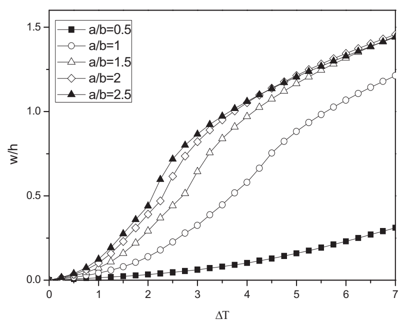

Fig. 3. Behaviors with variation of aspect ratio

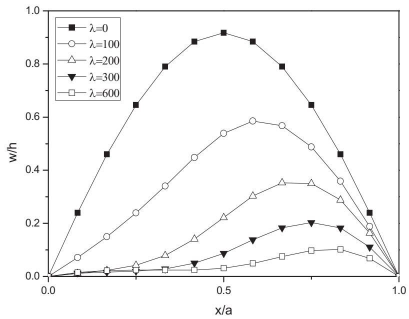

Fig. 4. Behaviors with aerodynamic load

The effects of airflow on deformed shapes of the all simply supported boundary model are presented in Fig. 4. It is center deflection along the x-direction at the point (y/b =1/2). As the aerodynamic pressure is increased, the deflection is decreased and the highest deflection point is moved backward. It can be known that as aerodynamic pressure is increased, the center of the model is gone downward at $\lambda = 300$. For the cases of over than $\lambda = 300$, there are sudden decreased in deformations at the center of the model. It is due to the dielectric layer is more ductile than face sheets, and thus center of the structure is more flexible at same temperature increasing.

4. Conclusions

In this study, the behavior of the multi-layer structure of a smart skin antenna induced by aerodynamic load is investigated. The smart skin structure which is consist of different characteristic such as Carbon/Epoxy, Glass/Epoxy, Honeycomb core and dielectric layer is studied. It is analyzed by the effect of area ratio of dielectric layer, aspect ratio of the structure and aerodynamic pressure. The thermo-mechanical behaviors are dependent on the design variable such as area ratio, aspect ratio and aerodynamic pressure.

Acknowledgements

This work is financially supported by the Brain Korea 21 project.

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